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# THERMAL IMAGING SYSTEMS

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This report examines the basic elements of a thermal imaging system. The four types of thermal imaging systems are described and the advantages and disadvantages of each are indicated.

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## INTRODUCTION

Before considering thermal imaging itself, we must first examine the elements of a pattern recognition system. The function of a pattern recognition system is to make a decision concerning the class of membership of the patterns with which it is confronted. A number of information translation processes take place between the time that a pattern is input and a decision is made by the system. These processes are summarized in figure 1. The functions of the blocks shown in this figure are described briefly as follows:

- The sensor is the measurement device that transforms the input patterns into a form suitable for machine manipulation. The preprocessor removes unnecessary elements of the measured data. The feature extractor then computes from preprocessed data the features required for classification. Finally, these features go into the classifier, which yields a decision concerning the class membership of the pattern being processed.

- Although the general form of these operations is specified by the system designer, each specific operation is characterized by variable parameters that must be adopted to a given pattern recognition problem. The adjustment of these parameters is carried out using sample patterns in what is called a learning process.

- Machining techniques are either of the supervised or unsupervised types. In the supervised type, the system parameters are estimated by algorithms that use sample patterns whose class membership is specified by the designer. The unsupervised learning approach is used when there is little prior knowledge about the pattern classes of a given problem.

## TWO-DIMENSIONAL TRANSFORMS ON IMAGES

Let us now consider the mathematical transforms of images for pattern recognition. Let f(x,y) be the brightness of intensity samples of a discretized image and F(u,v) be the transform domain of an image. The Hadamard transform of an image can then be given as

$$F(u,v) = \frac{1}{N} \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} f(x,y)(-1)^{\sum_{i=0}^{N-1} u_i x_i + v_i y_i} \qquad (1)$$

where

N = resolution of the digitized image

u, v, x, and y = ith binary variables in the expansion of the variables u, v, x, and y, respectively.

This transformation is unique in the sense that a second Hadamard transform on the function F (u,v) will result in the original image f(x,y). In addition, the one-dimensional version of the transform is obtained by N log N additions, if implemented on a digital computer.

Using the same notation as before, the discrete Fourier transform becomes

$$F(u,v) = \frac{1}{N} \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} f(x,y) \exp\left\{\frac{2\pi i}{N}(ux + vy)\right\} \tag{2}$$

This transform is unique in the sense that a second Fourier transform on the function $F_f(u,v)$ will result in a rotation of the original image, f (-x,-y). The computer implementation of the one-dimensional transform is obtained with an algorithm which requires N $\log_2 N$ and N/2 ($\log_2$(N)-2) + 1 multiplications.

Both the Hadamard and the Fourier domains can be analyzed for classes of identifying signatures by the decomposition of the image into two-dimensional Radamacher-Walsh or trigonometric orthonormal wave forms, respectively.

The properties of symmetry, dynamic ranges, and entropy of equation 2 will now be considered. The function f(x,y) describes the intensity of samples of an image's spatial domain. Since intensities are non-negative and real, f(x,y) must have the same properties. With this restriction on f(x,y), the Fourier domain becomes its own symmetric conjugate

$$F(u,v) = F^*(-u,-v) \tag{3}$$

This symmetry property requires that only half of the frequency samples need be retained for complete reconstruction of the original function, f(x,y).

Another property of the Fourier domain is its large dynamic range of possible values. If A is an upper band on f (x,y), then the range of allowable values at the origin is 0 to AN and the bound on all other frequency samples is +AN/2. While the dynamic range of possible values is extremely large, only a few points at a time can actually take on very large values. Parseval's relationship states that the total energies in the spatial and frequency domain must be equal

$$\sum_{x=0}^{N-1}\sum_{y=0}^{N-1}[f(x,y)] = \sum_{u=0}^{N-1}\sum_{v=0}^{N-1}|F(u,v)|^2 \tag{4}$$

Only a few spectral points, then, can be large because of the energy bounds. It is this redistribution of energy in the frequency domain that makes the energy matched filter relatively insensitive to those spatial frequencies with lower amplitudes which usually contain high frequency information.

A final property of the Fourier domain is obtained from information theory. The entropy of the Fourier domain is equal to that of the spatial domain. This means that information is neither gained nor lost when comparing the spatial and Fourier domains of an image. Although the entropies of the two domains are the same, equal bandwidths are not necessarily easily obtained. The Fourier domain contains larger valued numbers which require an increase in bandwidth for storage purposes. Consequently, a quantization technique must be developed if it is desired to represent the Fourier domain with the same number of bits as the spatial domain.

## IMAGE EVALUATION

If $\theta(x,y)$ is the output of spatial filter $h(x,y)$ with input $f(x,y)$

$$\theta(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(\zeta,\eta)\, h(x-\zeta, y-\eta)\, d\zeta\, d\eta \tag{5}$$

$$= f(x,y) * h(x,y) \tag{6}$$

and

$$\Theta(u,v) = F(u,v)\, H(u,v) \tag{7}$$

where

$*$ = convolution symbol

$\Theta(u,v)$, $F(u,v)$, and $H(u,v)$ = Fourier transforms of $\theta(x,y)$, $f(x,y)$, and $h(x,y)$, respectively.

Spatial frequency filtering can be used to remove noise or enhance, recognize, or evaluate images. The matched filter does pattern recognition as well as correlation of output data. The true matched filter maximizes the signal-to-noise ratio in a detection process when the noise perturbation is considered to be additive. If the signal to be detected is f (x,y) and the unknown input is

$$g(x,y) = f(x,y) + n(x,y) \tag{8}$$

then the matched filter response is given by

$$H(u,v) = \frac{F^*(u,v)}{N(u,v)} \tag{9}$$

where

$F^*(u,v)$ = conjugate of the Fourier transform of f (x,y)

$N(u,v)$ = power spectrum of noise process n (x,y)

A class of match filters can be described by the transfer function

$$Hp(u,v) = (-1)^p \frac{(u^2 + v^2) F^*(u,v)}{Np(u,v)} \tag{10}$$

where

$Np(u,v)$ = power spectrum of $p^{th}$ gradient operator on noise process n (x,y)

p = 0, for traditional energy matched filter

p = 1, for gradient matched filter

p = 2, for Laplacian matched filter

p = n, nth order gradient matched filter

The output of a filter in the presence of noise sampled at the origin is

$$e_{p_N}(0,0) = \int\int_{-\infty}^{\infty} (-1)^p \frac{(u^2 + v^2)^p F^*(u,v)}{Np(u,v)} G(u,v)\, du\, dv \tag{11}$$

Peak correlation occurs when the filter matches an image with itself in the absence of noise

$$\theta_p(0,0) = \int\int_{-\infty}^{\infty} (-1)^p |F(u,v)|^2 (u^2 + v^2)^p \, du \, dv \tag{12}$$

The ratio $\theta_{p_N}(0,0) / \theta_p(0,0)$ can then be defined as a correlation parameter, and an image evaluation decision can be based upon it.

## IMAGE PROCESSING

Many applications demand nothing more than the classification of the contents of any image presented to an automatic system. The classification may range from a single bit to many bits, such as counts, by type, of the number of objects of several categories observed in the image.

Other applications of image processing require image enhancement, in order to make otherwise obscure objects stand out. Some of the ways in which this is done is by increasing contrast or changing the gray-scale range, removing certain artifacts, and modifying the spatial frequency content of the imagery.

In still other applications, bandwidth compression is used in order to conserve on the precious commodity. As an example, consider a Mars communications system having a bandwidth of 10 bits/s. It would require one day to transmit a single 16 gray-level picture. In view of the high cost of this information, one would consider reducing the data to a one-out-of-ten code identifying the Martian scenery as being most like one of ten different terrain textures. The bandwidth compression ratio in this case, then, is 10:1. On the other hand many applications allow the removal of only true redundancy, reducing the compression ratio of 10:1 to 3:1.

## IMAGE PROCESSING IMPLEMENTATION

### Image Processing Classifications

Although there is an enormous variety of ways in which image processing can be implemented, it appears that nearly all hardware forms can be classified into one of four categories, depending upon the degree of parallelism inherent in the calculations being implemented. All conceptual approaches can be reduced to an equivalent network form. Because the object can appear anywhere on the image, it is assumed that the classification network must be repeatedly applied geometrically relative to many sampled elements in the image. These are called the image points. Within the network, the operator functions make calculations based upon inputs from their relevant image elements. These inputs are called the operator points. The basic hardware implementations and their process time, based on a 1 μs operation time, are shown in table 1. Each of these implementations will now be considered in turn.

Table 1. Image processing implementations

| Image point | Operator point | Time per frame |
|---|---|---|
| Serial | Serial | 21 days |
| Serial | Parallel | 1 hr |
| Parallel | Serial | 2 sec |
| Parallel | Parallel | 6 ms |

**Image Serial - Operator Serial**

The cathode ray tube (CRT) scanner and digital computer is the most versatile method for processing images. It has the ability of being programmed for any classification concept. In the case in which the operators represent spacial frequencies, the fast Fourier transform method can accelerate evaluation considerably. With the fast Fourier method, a typical transform process on a 256 by 256 element image takes about 5 min of computer time. Converting this figure to the same basis as table 1 yields 15 hr instead of 21 days. Although this is a great improvement, it is far from acceptable. One of the following systems must be implemented to obtain a practical system.

**Image Serial - Operator Parallel**

Various methods have been devised for generating the operator connections in parallel, and scanning over the image area serially. A typical technique employs an optical mask to mechanize the weighted sum of input values of the linear threshold function together with a scanned beam to serially mechanize the threshold.

**Image Parallel - Operator Serial**

The effect of performing a single operation over an entire image can be accomplished by sequentially shifting the image in amounts corresponding to the operator connections and at each position adding the image to itself. This type of system can be implemented by electron imaging devices, which provide temporary parallel integration of a sequence of exposures. Another implementation is with a parallel computer. In such a computer fields of data can be shifted in parallel, and simple logic processes can also be performed in parallel. By programming the sequence of logic operations the usual arithmetic functions, as well as any threshold operations, can be generated.

### Image Parallel - Operator Parallel

A truly parallel system can be made with optical and photographic methods. The main disadvantage of the implementation is the long time required to process the film used for intermediate storage of processing results. The solution to parallel-parallel processing lies in the combination of parallel optics and parallel image amplification.

## THERMAL IMAGING

### Introduction

The molecules of a medium absorb infrared (IR) radiation at characteristic wavelengths. In the case of the atmosphere, the chief absorbing constituents in the IR band are carbon dioxide, water vapor, and ozone. The transmission curve for IR through the atmosphere is shown in figure 2. It is seen that there are two windows in the range of 3 to 5 μm and from 8 to 13 μm. For efficient transmission, the thermal system must operate in one of these windows.

A block diagram of a thermal imaging system is shown in figure 3. The lens system works just like an optical lens system with the important difference that the lenses are made of a material that transmits infrared. The scanner and detector, which will be described more fully, are the heart of the system. The output of the detector is a video signal, and in many cases has the form of a standard television signal. The signal processing is, therefore, similar to television signal processing and the display appears on a television monitor.

### Scanning and Detecting

The ideal detector consists of a mosaic of elements resembling the eye and not requiring scanning, since the whole scene appears on the array. A resolution of 0.5 mrad and a field of view of 20 deg requires approximately half a milion picture points. Each detector must have its own preamplifier and each channel must have an identical response.

Going to the other extreme, one could have a single element that can be scanned across the whole scene (fig. 4). For television picture quality, an information picture bandwidth of about 5 MHz is required. The cadmium mercury telluride photoconductor has one of the fastest response times, but its bandwidth of around 200 kHz is clearly inadequate.

An array of detector elements, therefore, must be used to get both high thermal sensitivity and picture quality. The use of the detector array with N elements improves the signal-to-noise ratio by the $\sqrt{N}$. This is because the sampling rate for any one picture is increased by a factor of N; the signal is increased by N times and the incoherent noise by the $\sqrt{N}$.

The layout of a parallel array is shown in figure 5. It is mounted vertically and scanned horizontally. The whole scene may be scanned in one sweep provided the array contains enough elements for adequate resolution. The same result can be obtained with a series of continuous swathes from top to bottom (fig. 6). The output of each detector is amplified and displayed sequentially on a CRT or light emitting diode (LED) display. A typical detector system of 150 elements; each 50 µm square, a frame rate of 25/s, a 300 line picture, and suitable optics; would have a sensitivity of 0.5 C.

## Thermal Detectivity

The simplest method of forming a thermal image using photon detectors is to scan all points of an image of the scene and in turn with this modulate the brightness of the corresponding display. Using a scanning system has the advantage of ac coupling; only the signal variations are passed, while the large dc pedestal is rejected. An artificial dc level is added by an internal reference and the available contrast is expanded over the dynamic range of the display. The contrast expansion requires a good signal-to-noise ratio; detector noise sets a lower limit to the smallest detectable temperature difference.

An equation for the temperature sensitivity of an image can be derived from the detector response, the collecting power and efficiency of the optics, and the scanning system. We proceed as follows:

$$NEP_{\lambda} = AH_{\lambda} \tag{13}$$

where

NEP = noise equivalent power, w

A = detector area, $cm^2$

H = incident flux at wavelength $\lambda$ for unit S/N, $w/cm^2$

Because using NEP has some inconvenience, the quantity D* was adapted to describe detector performance, which includes NEP and also normalizes for the inverse square root dependence of the photon detector on area and bandwidth.

Thus

$$D_\lambda^* = \frac{(AB)^{1/2}}{NEP_\lambda} = \frac{B^{1/2}}{A^{1/2}H_\lambda} \tag{14}$$

where

$A$ = area, $cm^2$

$B$ = bandwidth, Hz

$D_\lambda^*$ = detectivity, $Hz^{1/2}w^{-1}cm$

The bandwidth for a system employing a single element detector is

$$B = \frac{1}{2}\frac{\theta\phi f}{m^2\varepsilon} \tag{15}$$

where

$\varepsilon$ = scanning efficiency

$\theta$ = vertical field of view, rad

$\phi$ = horizontal field of view, rad

$f$ = frame frequency, Hz

$m$ = angular resolution, $rad^2$

If a detector array with N elements is used in parallel scan, the bandwidth per channel becomes B/N.

For a temperature difference in a scene to be just detectable by a scanning imager, $H_\lambda$ becomes the flux change at the detector at which signal strength equals noise. This is given by

$$H_\lambda = \frac{(\partial W/\partial T)_\lambda \, \Delta T \text{ ta to}}{4F^2} \tag{16}$$

where

F = focal length/diameter

ta = atmospheric transmission at wavelength $\lambda$

to = optics transmission factor

$\Delta T$ = temperature difference in scene to give $H_\lambda$

$(\partial W/\partial T)_\lambda$ = differential radiance from a black body at scene temperature

Substituting $H_\lambda$ in equation 14

$$D^*_\lambda = \frac{4F^2 B^{1/2}}{A^{1/2} (\partial W/\partial T)_\lambda \, \Delta T \text{ ta to}} \tag{17}$$

or

$$\Delta T = \frac{4F^2 B^{1/2}}{A^{1/2} \text{to} \, (\partial W/\partial T)_\lambda \text{ ta } D^*_\lambda} \tag{18}$$

$\Delta T$ was derived for the wavelength $\lambda$. If the effect of all wavelengths is included, the minimum detectable temperature difference becomes

$$NE\Delta T = \frac{4F^2 B^{1/2}}{A^{1/2} \text{ to} \int_0^\infty \left(\frac{\partial W}{\partial T}\right)_\lambda \text{ta } D^*_\lambda \, d\lambda} \tag{19}$$

We now define M* as a figure of merit for detectors used in thermal imaging

$$M^* = \int_0^\infty \left(\frac{\partial W}{\partial T}\right)_\lambda ta\, D^*\, d\lambda \qquad (20)$$

then

$$NE\Delta T = \frac{4F^2B^{1/2}}{A^{1/2}\, to\, M^*} \qquad (21)$$

From equation 21 it is apparent that the greatest gain in sensitivity can be achieved by minimizing F, but the need to maintain resolution at the edges of the field-of-view limits this. Temperature sensitivities, NEΔT, around 0.1 C are typical, but higher sensitivities to 0.001 C can be achieved for special purposes.

## RESULTS

### General Description

A real time thermal imaging system has an integral display using LED in a geometrical configuration corresponding to the detector array. The LED are driven by the corresponding detector outputs and the image is created by scanning the LED from the back of an IR mirror. The more common type of system has electronic processing that converts the amplified detector outputs into a sequence and form for television type display. From the theory presented in this report, four basic types of scan-imaging systems result.

### Serial Scan - Standard Video

A serial scan--standard video system is shown in figure 7. It is the most direct way for generating standard video and has the advantage of not requiring multiplexers and scan converters. Another advantage is the low cost for displays, video recorders, symbol generators, data retransmitters, and automatic target rackers.

### Serial Scan - Parallel Video

A basic serial scan--parallel video system is shown in figure 8. A two-dimensional array of detectors is coupled one-for-one to a similar array of LED. In this system, the inherent integration of the observer's eye produces the image-smoothing effect associated with serial scanning and combines this with the simplicity of a directly viewed LED array.

## Parallel Scan - Standard Video

A parallel scan--standard video system is shown in figure 9. This system requires a collecting converging lens, a two-sided scanner, an LED array, a vi[illegible] and a CRT. The video is converted to standard video format by electro-optical m[illegible]plexing with a television camera. For proper operation, perfect synchronization of the frame rates of the thermal and television scans is necessary, and matching of the dynamic ranges of the two devices is delicate.

## Parallel Scan - Parallel Video

The simplest multidetector system is the parallel scan--parallel video system (fig. 10). This system requires only a collecting converging lens, a two-sided scanner, a detector array, a set of amplifiers, display drivers, and an eyepiece. In the system, a convergent beam scanner uses one side of an oscillating thin mirror to generate the thermal scan and the other side to generate the visible scan. The detector signals are amplified and shaped to appropriately drive the visible light emitters. The mirror and eyepiece magnify and focus the LED scan for the observer.

The advantages of this system are that no scanner synchronizer is needed, the scanner requires little power, and the display is compact. Its disadvantages are that only one person may observe the display, loss of nay part of channel causes loss of one line of video, all channels must be balanced individually and controlled simultaneously, and video waveform shaping must be performed in each channel. Despite its disadvantages, the parallel - parallel system is a very cost effective way to achieve a small viewer.


Figure 1. Pattern recognition system

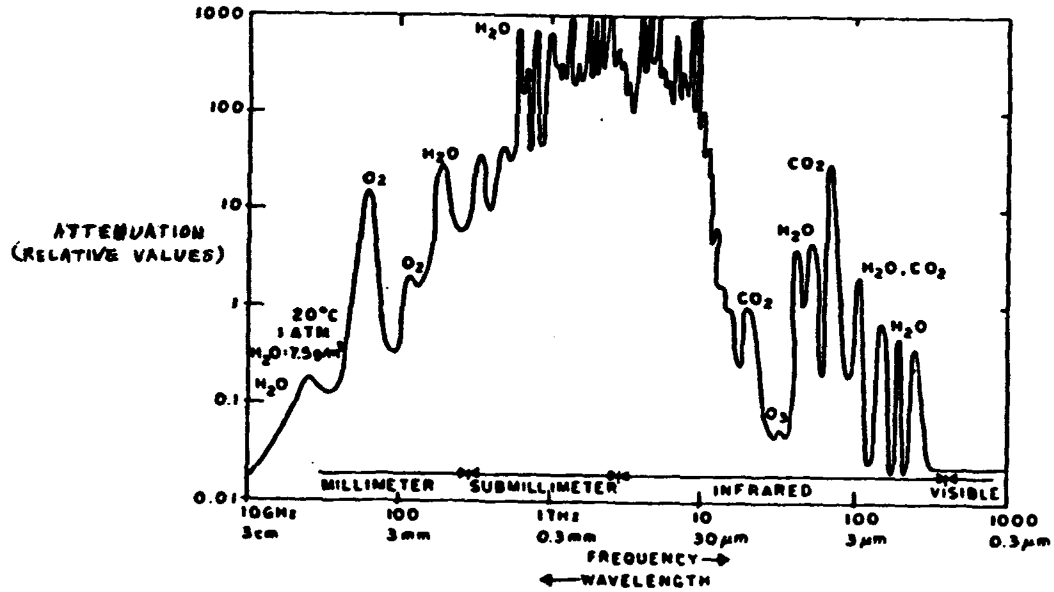


Figure 2. Clear weather atmospheric attenuation of electromagnetic radiation

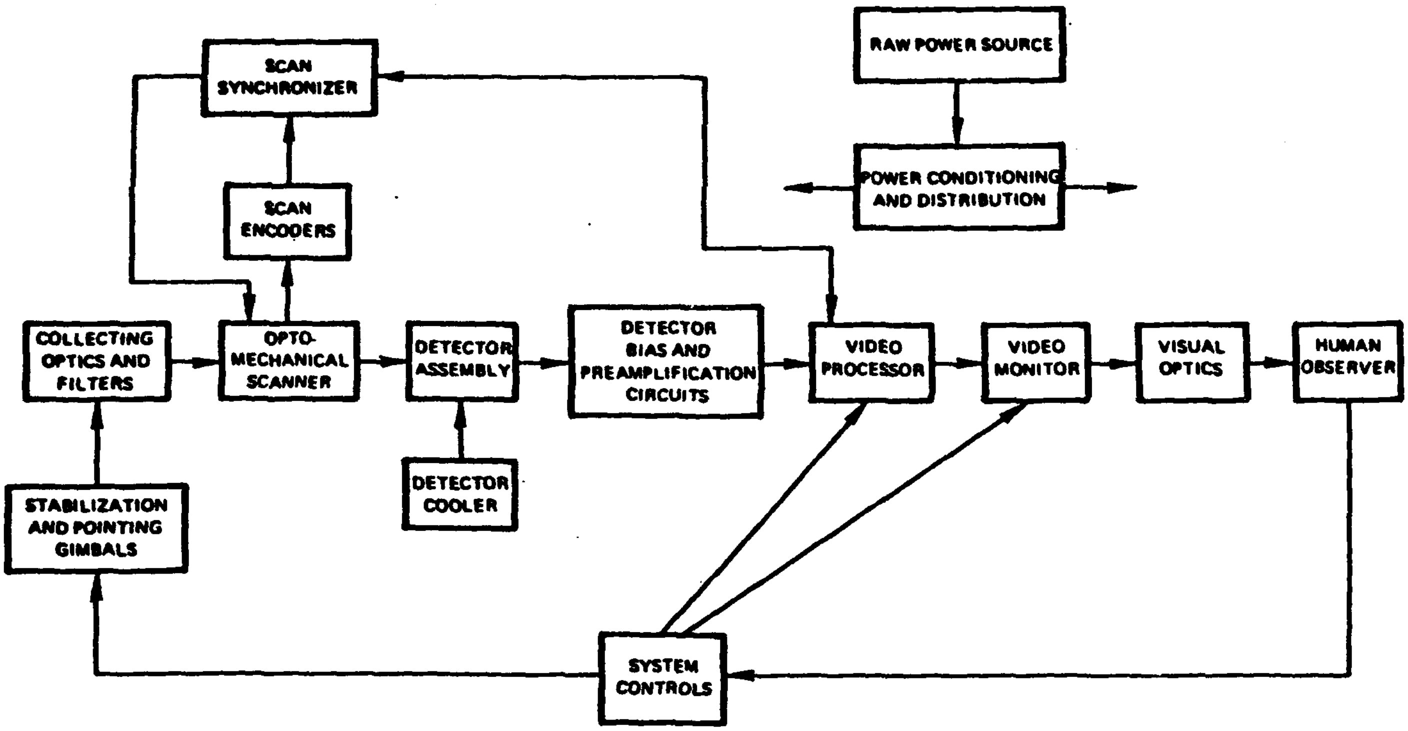


Figure 3. Thermal imaging system

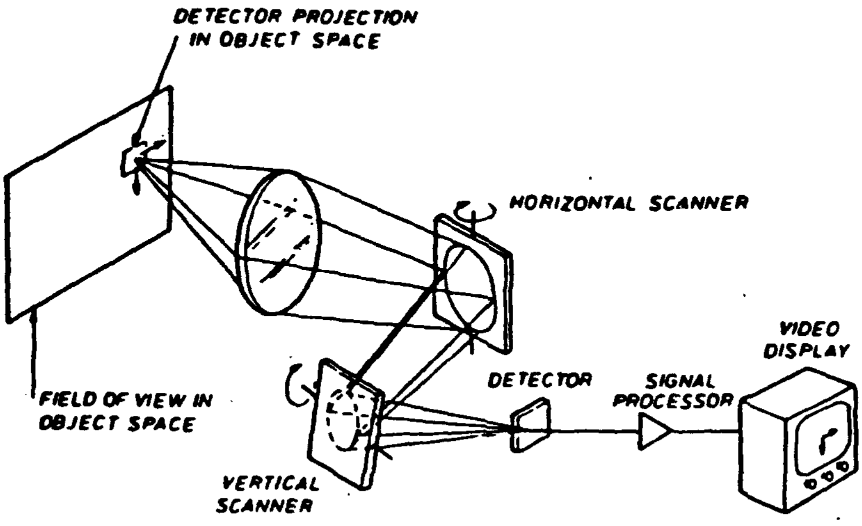


Figure 4. Single detector serial scanning

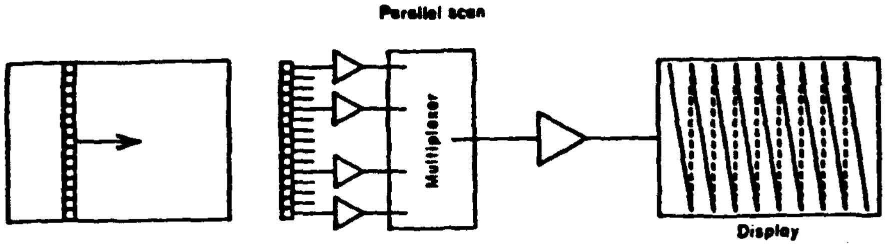


Figure 5. Parallel scanning

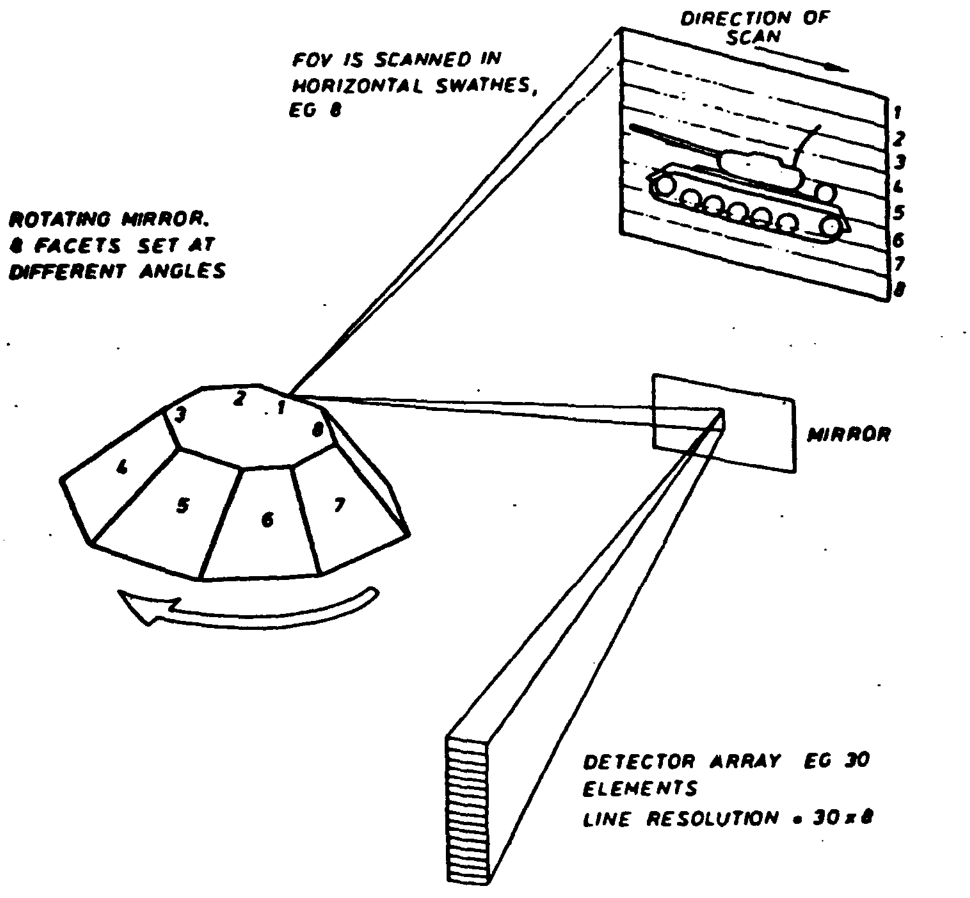


Figure 6. Segmental parallel scanning

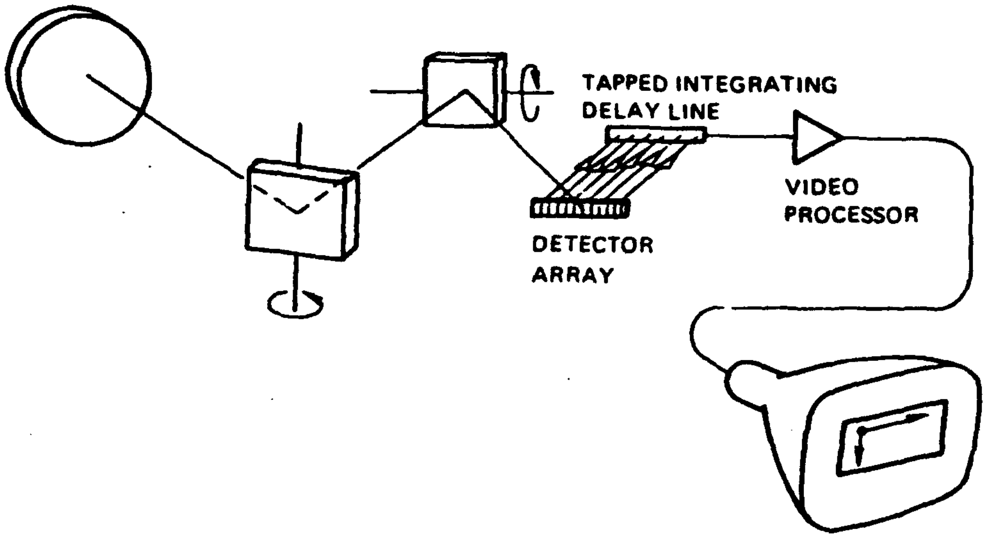


Figure 7. Serial scan - standard video system

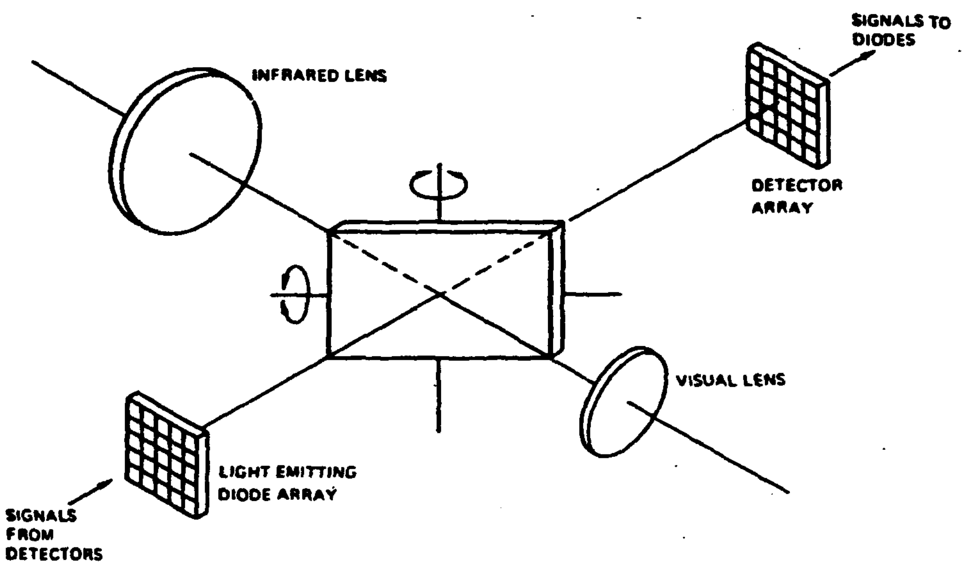


Figure 8. Serial scan - parallel video system

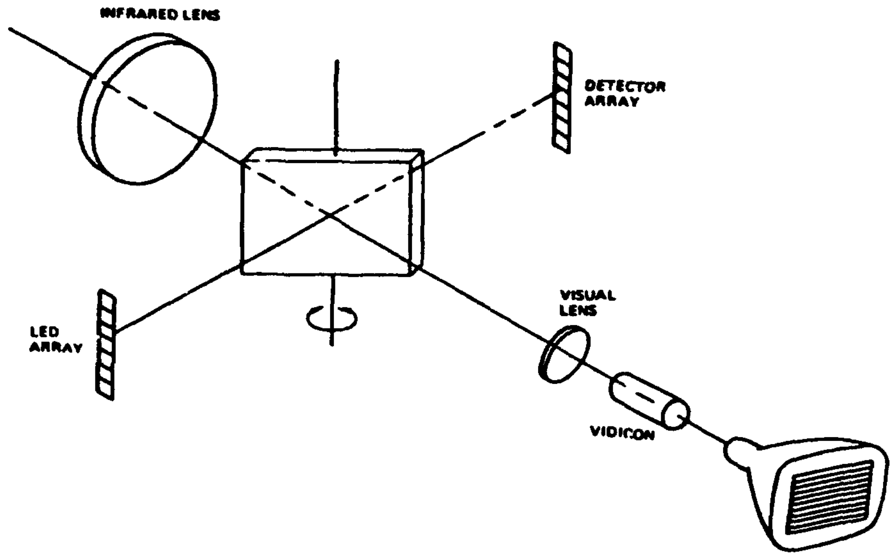


Figure 9. Parallel scan - standard video system

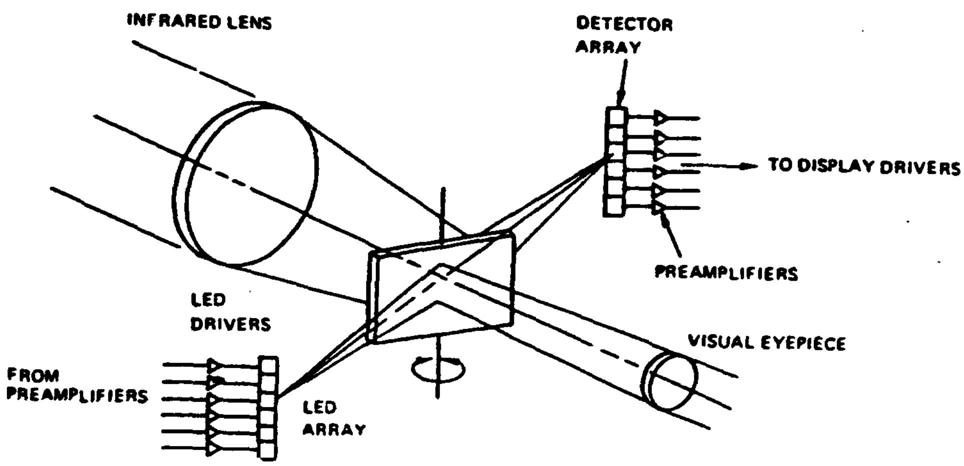


Figure 10. Parallel scan - parallel video system

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